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DESIGN AND DEVELOPMENT OF A SEGMENTED MAGNET HOMOPOLAR TORQUE CONVERTER

C. J. Mole, et al

Westinghouse Electric Corporation

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DESIGN AND DEVELOPMENT OF A SEGMENTED MAGNET HOMOPOLAR TORQUE CONVERTER

Semi-Annual Technical Report for
Period Ending November 30, 1972

Submitted to ARPA in December, 1972

Principal Investigator:

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This program is for the research and development of a new mechanical power transmission concept; the segmented magnet homopolar torque converter. The purpose of this device is to convert unidirectional torque of constant speed (such as from a steam turbine prime mover) into variable speed output torque in either the forward or reverse directions. The concept offers an efficient, lightweight low volume design with potential application over a wide range of speeds and power ratings in the range from hundreds to tens of thousands of horsepower. This machine concept can be applied to commercial and military advanced concept vehicles for both terrain and marine environments.

This report pertains to the initial study phase of a proposed 45 month program to design and develop this machine. In this phase all of the technical problems are being reviewed, the machinery concepts and applications are being studied, and a detailed technical plan is being evolved for the entire program.

The program places particular emphasis on the materials technology of liquid metal current collection systems for the reason this is essential for the success of the homopolar machine concept.

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Approved by: C Mole
C. J. Mole, Manager
SC Electric Machinery Systems
(Electro-Mechanical Division)

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SECTION 1
INTRODUCTION AND SUMMARY

1.0 GENERAL

This is the first semi-annual technical report and covers the work performed from program inception June 1, 1972 through November 30, 1972.

1.1 BACKGROUND

This is a new program for the research and development of a new Westinghouse proposed mechanical power transmission concept: the segmented magnet homopolar torque converter. The purpose of this device is to convert unidirectional torque of constant speed (such as from a steam turbine prime mover) into variable speed output torque in either the forward or reverse directions. The concept offers an efficient, lightweight low volume design with potential application over a wide range of speeds and power ratings in the range from hundreds to tens of thousands of horsepower. Initial analysis indicates that this machine concept can be applied to commercial and military advanced concept vehicles for both terrain and marine environments.

1.2 OBJECTIVES

1.2.1 General

This 8-month study constitutes the initial phase of a proposed 45 month program to design and develop the segmented magnet homopolar torque converter (SMHTC). In this phase all of the technical problems will be reviewed, the machinery concepts will be studied, and a detailed technical plan will be evolved for the entire program.

Particular emphasis will be placed on the materials technology of liquid metal current collection systems for the reason this is essential for the success of the homopolar machine concept.

1.2.2 Summary of Objectives

The objectives of this Phase I program are summarized more specifically as follows:

- Review the state-of-the-art of liquid metal and solid current collection systems for segmented homopolar machines including motors, generators, and torque converters.
- Review and select promising applications for the segmented magnet machines and torque converters.

- Select promising liquid metals, and current collection system conceptual designs for these promising applications.
- Evolve a conceptual design for a 6000 HP torque converter using the segmented magnet machine.
- Develop a program to: a) Solve all of the problems relating to current collection systems for segmented magnet machines; b) Demonstrate the solution of the problems in a small segmented magnet homopolar machine; c) When successful demonstration is completed utilize the technology in the development to design, construct and test a segmented magnet homopolar torque converter.

1.2.3 Summary of Technical Tasks

This program is divided into the following technical sub tasks:

1) Segmented Magnet Homopolar Torque Converter (SMHTC) System Studies. SMHTC system studies of various possible machine configurations. A conceptual design will be prepared of a 6000 HP machine to deliver constant torque from zero speed to 200 RPM in forward and reverse directions, from a 1200 rpm input shaft.

2) Application Study

   A survey will be made of the most promising applications for segmented magnet torque converters, motors, generators.

3) Liquid Metal Current Collection Systems

   A study will be conducted of liquid metal current collection system technology. The preferred system and liquid metal shall be identified for the segmented magnet homopolar machine arrangement. Various methods will be investigated for removing contaminants from the liquid metal system including electrolytic reduction, closed-loop and exterior clean-up systems.

4) Materials Study

   The materials requirements and related problems will be identified for the segmented magnet homopolar machine. Particular emphasis will be devoted to the long term compatibility problems between the selected liquid metal and the electrical conductors, insulation and structural materials in the system.

5) Segmented Magnet Homopolar Machine Design

   A conceptual design will be evolved for a segmented magnet homopolar machine (SEGMAG) for operation as a motor or generator. This machine will be the test vehicle for current collection system technology, and will demonstrate the concept. The machine rating will be greater than 300 hp.

6) Seal Study

A study of the sealing problems between the liquid metal, bearing oil system, and the environment shall be conducted. Seal system conceptual designs will be evolved for both the SMHTC and SEGMAG machines.

7) Plan for Phase II

A plan shall be evolved to complete the development of the segmented magnet homopolar torque converter. This plan will identify all of the technical problems to be solved, the research and development tasks required to solve these problems, and the resources and manpower required to complete the development.

1.3 SUMMARY OF CURRENT PROGRESS

The progress of each of the technical tasks on this program is summarized separately in the following paragraphs:

1.3.1 Segmented Magnet Homopolar Torque Converter (SMHTC) Studies

A need exists for a device that will accept high speed, low torque mechanical energy from a prime mover such as a gas turbine and convert it to variable low speed, high torque mechanical energy to drive a ship's propeller. The device proposed is a segmented magnet homopolar torque converter (SMHTC) which uses a DC segmented magnet (SEGMAG) generator and motor for this energy conversion. A design study is being made to develop the parameters for large machines (30,000 HP) and smaller prototype units (6000 HP). Design studies have been completed for the units and a conceptual design layout is being prepared for the prototype machine.

1.3.2 Application Study

Section 3 discusses in some detail a number of applications which are potentially feasible. All applications are contingent upon proper solution to the problem of current collection. The use of liquid metal to transmit simultaneously large quantities of electrical current and large quantities of heat flow from the rotating armature must be solved in a reliable and safe fashion to realize these applications. While considerable progress has been made during Phase I of this study, such progress has been relevant to the basic research involved with such a current collection system. The current collector must be tested in its expected environment, i.e., the conduction of heat and current in the presence of magnetic field phenomena.

1.3.3 Liquid Metal Current Collection Systems

The development of liquid metal current collection systems is the most important technical problem that must be solved if machines utilizing such

systems are ever to be realized. Even though some work has been done on this subject at a number of sites all over the world, the results of these efforts have not as yet produced the desired ends. Literature review and site visitation have revealed that the magnitude of the problem area and the vagaries of liquid metals in this application are not fully appreciated nor fully confronted. Considerable analytical work as well as experimental work are required to understand the forces acting on liquid metals in high current density collectors. Moreover, the results of these efforts must interface with both the stringent purity and handling requirements on the liquid metal and associated cover gas and the requirements of machine design.

While NaK, sodium-potassium alloy, appears to be the most suitable liquid metal under most anticipated operating conditions (i.e., it yields the smallest power losses), GaIn, gallium-indium alloy is a suitable back-up choice and under low speed-high field conditions as in a torque converter at 200 rpm, it even yields lower losses than NaK.

Analytical work has shown that confinement of the liquid metal in an annular gap under constant speed condition (as in a generator at 3600 rpm) is a much less severe problem than when speeds are changing or when even machine reversal is required (i.e., shaft rotation goes through zero speed). This latter situation is still receiving continued investigation and analysis. Experimental work on all aspects will be required to confirm analytical predictions.

The advent of homopolar machines with liquid metal current collectors will make practical a new class of machine with numerous possible applications as cited in Section 2, many of which have direct bearing on current and future DOD needs. Future work will be required to develop the individual applications as well as to improve and optimize collector design and understanding.

1.3.4 Materials Study

The selection of materials (conductors, structurals, and insulators) for use in homopolar machines containing liquid metal current collectors must give careful consideration to long term compatibility effects under all operating or maintenance conditions and to the special reactive nature of liquid metals. While a literature review of pertinent information is providing general guidelines on materials selection, the paucity of reported work with homopolar machines will require significant experimental work to establish both how liquid metals affect materials in this application as well as how the materials affect the liquid metals (i.e., contamination from outgassing). Lists of candidate materials selection strategy which maximizes the capabilities of long term, safe operation for liquid metal current collectors will have profound benefits on land based and ship propulsion systems and on the development of efficient and compact dc energy sources. Once the base technology of liquid metal current collector systems is established, additional work will be required to apply the developments to specific areas.

1.3.5 Segmented Magnet Homopolar (SEGMAG) Machine Design

In high current DC machines such as acyclic or homopolar units, the current collection system design is critical because of the current density and leakage flux in the system. Separate subassembly tests can be performed to evaluate various collector designs, however, the true test is operation within a machine. To provide this test vehicle a segmag machine is being designed to evaluate current collection technology and to demonstrate the segmag concept. A preliminary design layout for a demonstration unit is nearing completion.

1.3.6 Seal Study

The successful application of homopolar machinery relys on the use of liquid metal as the current collector. For the liquid metal to function efficiently as a current collector, it is imperative that its oxidation, through exposure to air or moisture, be prevented. A basic requirement, therefore, of homopolar machine design is to blanket the machine with an inert cover gas and to confine that cover gas to the machine's environment by means of a containment vessel. A direct result of this requirement is the need of a sealing system at that location where the machine's shaft penetrates the containment vessel. This sealing system must perform two functions. First, it must prevent excessive loss of the inert cover gas to the outside environment. Second, it must effectively stop any leakage of air from the outside environment into the containment vessel, thereby avoiding oxidation of the liquid metal current collector.

A second sealing requirement related to homopolar machinery - specifically, motor applications - is associated with the current collector itself. In the case of a generator, the very nature of its operation (constant speed and continuous), holds the liquid metal current collector in the collector gap by the centrifugal forces exerted upon it due to rotor rotation. Motor applications, however, require variable and low speed capabilities, as well as the ability to reverse or initiate rotation from zero speed. To insure efficient motor performance under all modes of operation, it may therefore be necessary to contain the liquid metal in the collector gap under those operating conditions where centrifugal forces are incapable of performing this function. Consequently, various sealing techniques and seal materials must be investigated to determine their capability of confining the liquid metal to the current collection zone.

SECTION 2

SEGMENTED MAGNET HOMOPOLAR TORQUE CONVERTER (SMHTC) SYSTEM STUDIES

2.0 OBJECTIVES

The objective of this program is to investigate a 30,000 HP torque converter capable of transmitting energy from a 3600 rpm prime mover to a propeller shaft whose speed varies from a forward speed of 200 rpm to a reverse speed of 200 rpm. This concept will be demonstrated with a conceptual design producing 6000 HP at 200 rpm from a 1200 rpm drive unit. The output shaft shall deliver constant torque from zero to 200 rpm in forward and reverse direction. The concepts demonstrated in this machine will be extrapolatable to the larger unit.

2.1 PRIME AND RELATED WORK

The SMHTC concept was derived from a unique modular DC homopolar machine being investigated at Westinghouse. This machine, known as a segmented magnet homopolar machine (Segmag) uses series connected DC modules to obtain the design output. The characteristics of segmags is being investigated on another contract (N000 14-72-C-0393).

2.2 CURRENT PROGRESS

The electrical analysis of the large (30,000 HP) and small (6000 HP) machines have been completed. The electrical analysis for the large unit was performed to determine the approximate size and weight for the unit. Two conceptual design layouts are being prepared for the 6000 HP machine. The radial SMHTC design uses a segmag generator mounted within a segmag motor as shown in Figure 2-1. The design uses a stationary stator located between the rotating drive shafts. The stator is separated magnetically to prevent interaction of the excitation from the motor and generator portions of the machine. The conceptual design layout for the radial design is 70% complete.

The axial design uses an inline segmag generator and motor. This design is feasible if high current buses from the generator to the motor can be limited to approximately 12 inches. Design layouts are being prepared for this concept to determine if this objective can be achieved.

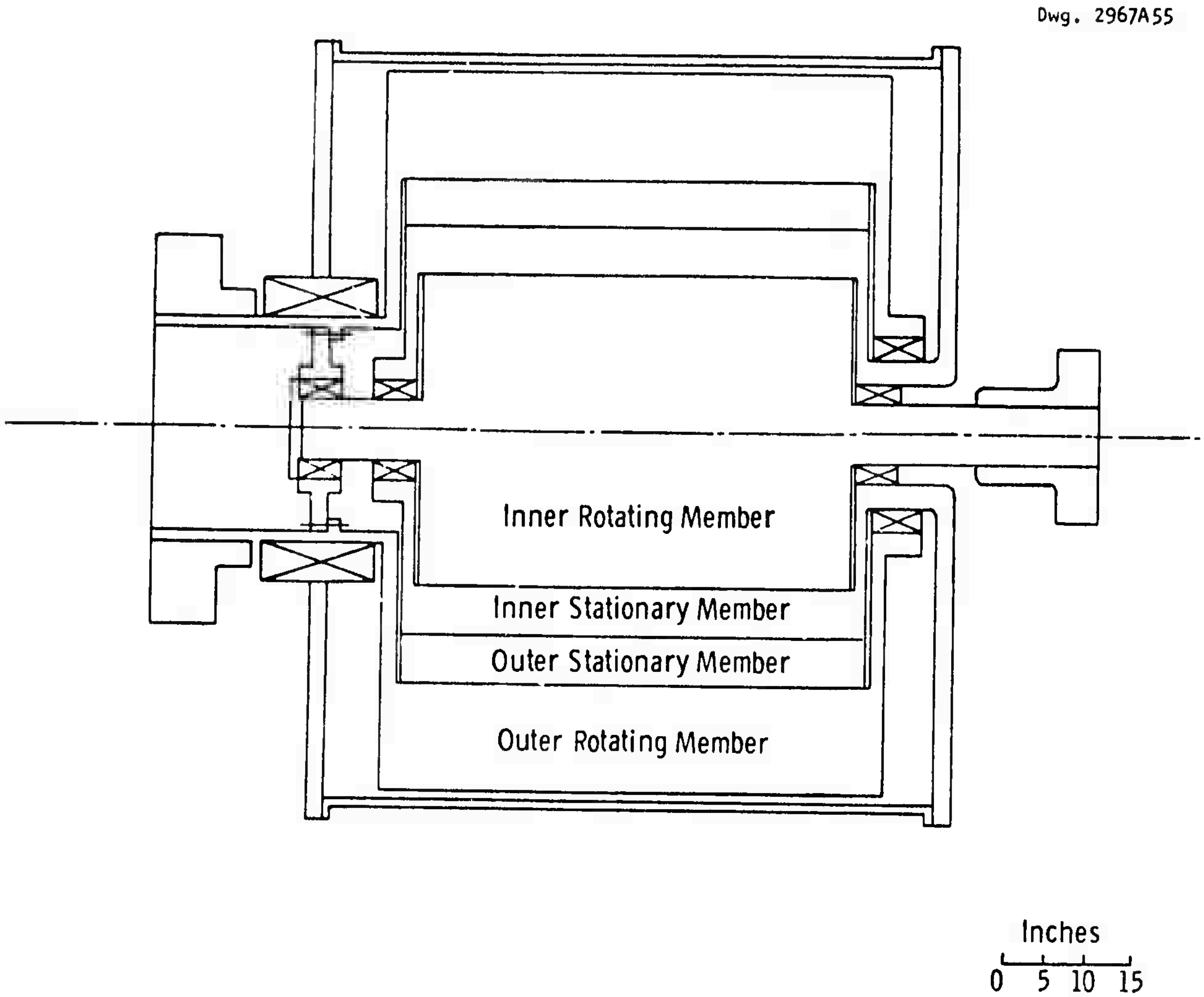

Figure 2-1 — Feasibility design of a segmented magnet homopolar torque converter.

SECTION 3
APPLICATION STUDY

3.1 APPLICATION STUDY

Application studies of SEGMAG generator and motor configurations and of the integral SMHTC combination have been conducted. This discussion will use the following definitions:

1. SEGMAG refers to the segmented magnet homopolar machine, configured as either generator or motor in a given installation. A system composed of such components will necessitate an external system of transmission bus, limited in its current-carrying capacity by losses, size and weight tradeoffs.

2. SMHTC refers to the segmented magnet homopolar torque converter, a combined unit of generator and motor of the SEGMAG variety, connected by high current capacity bus bars integral in a given structure. The unit may be constructed of concentric SEGMAG units, end-to-end units, or offset units in parallel or right-angle geometry.

3.2 SPECIFIC APPLICATIONS

3.2.1 Ship Propulsion

The use of electrical propulsion in ships has long been suggested as a means of reducing a high speed, low torque prime mover to a low speed, higher torque propeller load. Such reduction is necessary to maximize system efficiency. The use of electric drive gave way in the late 1930's to marine reduction gearing, the latter offering an advantage in lighter weight, less required volume, and higher efficiency. The SMHTC is suggested as an alternative to this marine gearing, pending the satisfactory solution of the current collection problem. As a dc machine system, it offers maximum torque to propeller at any speed in reversal and in acceleration. As a self-contained unit, it does not have the problem of high currents circulating in large dc power bus bars that might weigh on the order of 60,000 lb/100 ft for a 30,000 hp system.

The argument may be offered that the SMHTC offers electric propulsion without the advantage of flexibility of machinery location. In essence, the SMHTC uses electrical power as the conversion medium from prime mover to propeller, but is designed as an alternative for marine reduction gearing with the benefit of torque and power control characteristics of dc machinery. The application of SMHTC to propulsion, with typical characteristics, are given below:

- Matches any single prime mover; steam, gas turbine, diesel, In several applications, can combine twin prime movers.

- Reverses by control of low power field excitation rather than reversing turbine required in mechanical gearing systems.

- Delivers full power in reverse versus maximum of 40% reverse power of geared ships with reversing turbines.

- Control of generator and motor field will allow matching variable displacement load condition of ship.

- Efficient utilization of unidirectional prime mover.

- No more geometrically constrained than marine gearing.

Typical Application Parameters

hp	rpm	Prime Mover	Typical Application
5-10,000	150-300	Diesel, gas turbine	Tug or pusher boat
15,000	200	Steam turbine	Submarine
30,000	200	Steam turbine	Advanced submarine
40,000	180	Steam, gas turbine	Single screw naval escort
40,000	180	Steam, gas turbine	Twin screw naval frigate
40,000	180	Steam, gas turbine	Sea control ship
45,000	80	Steam turbine	LNG, tanker

These applications appear to be technically feasible, but are speculative in the sense that full design and economic analysis of the total propulsion system is required to replace the "existing" or more conventional system normally ordained for such ships.

3.2.2 Torpedo Drive

This application has potential with regard to the possible development of self-contained torque converters or SEGMAG motors for the propulsion of torpedo or other remote underwater devices. Typical requirements and physical parameters associated with such systems are listed below.

- Power rating approximately 500 hp
- Contrarotating screws, $\pm$ 1800 rpm
- Low specific weight for energy conversion, 1 to 2 lb/hp
- Compatible with either battery or chemical turbine source

- Total system weight fraction 10% of total
- Available volume 20 in. in diameter, 20 in. long
- Possibly short duration of run for torpedo, on the order of 10 minutes
- Possibly expendable machinery for torpedo or remote underwater devices
- Necessarily high efficiency to lower effect upon energy source

The application of SMHTC to the chemical turbine or to SEGMAG motor for the battery driven case appear to be feasible. Specific weights for the high speed case are on the order of 1.0 lb/hp or less at 800 rpm and decreasing to the order of 0.4 lb/hp for higher speeds of 3600 rpm. The decreasing diameter and the high speed of chemical prime movers are compatible with the SMHTC concept. The nature of design of the integral SEGMAG motor parameters is as follows:

- SEGMAG is a dc machine
- Dc voltages are compatible with existing battery voltages
- Excitation requirements are dc
- Low cost is anticipated for the basic structure
- Rapid response to control of excitation is inherent for non-superconducting homopolars

Solution of the current collection problem will be required to permit compatibility of liquid metal with the drive system and environment of the mobile platform. In the case of the expendable torpedo, it is envisioned that the device could be armed with liquid metal as it is armed with payload, prior to delivery. In this case storage is safe. Liquid metal could be sealed in an internal reservoir until activated. The solution of the current containment would be more of a short-term nature than is the reliability required for propulsion. This is due primarily to the short duration of delivery, on the order of 10 minutes.

3.2.3 High Power Pulsing Generators

This application appears extremely promising in the area of stored energy conversion. In a typical case of energy storage, the rapid rate of pulse and the resiliance to undergo a severe frequency of pulses is inherent in the SEGMAG generator. The rapid rate of response to a signal follows from the typicall small excitation signal required to generate a high power signal. This will be possible in the non-superconducting SEGMAG homopolar generator. The inductance and high stored magnetic field associated with the superconducting SEGMAG do not appear to be easily overcome by conventional excitation techniques.

Typical pulsing requirements for further conversion are:

- Pulse width of 11 seconds duration
- Power level of 550 x 10^6 joules
- Rise and fall times of 1 second or less
- Frequency of one pulse per minute

3.2.4 Heavy Vehicle Drive

This application has potential for a wide class of heavy vehicles, including military vehicles of all types. An industrial counterpart of potential benefit is the heavy, earthmoving vehicle, of typical minimum size characteristic ballasted weight 44,000 lb, requiring nominally 300 hp to propel the vehicle at 40 mph.

Recent R&D efforts in the propulsion of vehicles of the sort described above have involved the "electric wheel" concept, utilizing a combination of high speed (39,000 rpm), high frequency (3200 Hz), single shaft gas turbines, ac synchronous generator converted to ac induction motors through solid state cycloconversion equipment. Most systems under development for military equipment utilize ac generators at high rpm, ac motors at high rpm (3,000 to 30,000) for constant horsepower through reduction gearing (typically 140:1) to a vehicular speed of approximately 215 rpm.

The SMHTC and various combinations of SEGMAG generators and motors appear as feasible alternatives to the propulsion system described above. Inverter and/or cycloconverter circuits were utilized to generate the high torques and wide speed range required for a propulsion system. The use of high speed prime movers also precluded conventional dc generation from the viewpoint of excessive weight and volume. These characteristics are feasibly matched by the SEGMAG and SMHTC dc machinery concepts. Although more detailed study is required to determine the competitive status of this application, the high power densities of the SEGMAG units indicate feasible application. The current collection system must be solved, with the added complexity of miniaturization being introduced by the desire to provide high speed generators at power levels in the range less than 1000 horsepower.

The use of electrical transmission in ground vehicles of this type offers the advantage of allowing the evolution of new vehicular forms around the flexibility of location of prime mover from motor connection to the wheel. This has the distinct advantage of placement of components to allow full articulation of the vehicle concept. An advantage to an earth-moving vehicle application follows from the gain in gradability of the vehicle due to smooth and controlled manner of applying tractive effort to ground. The overall system would be attractive from the good utilization of the gas turbine engines and high efficiency of the SEGMAG motor/generator and SMHTC concept over the operating range. Several advantages would be offered to the vehicle class, including remote powering and control capability, accurate steering control, and mechanical isolation of drive components.

Future applications lie in the area of extremely large vehicles, of current size near 645,000 lb under full load. These vehicles employ two 550 hp traction motor operating over the range 0 to 2400 rpm, delivered through 35:1.1 reduction gear to provide vehicular motion at 0 to 70 rpm.

3.2.5 Variable Speed Input/Constant Speed Output Aviation Drives

This application has been utilized to supply fixed frequency electrical power on mobile platforms, i.e., aircraft or ships, from variable speed prime movers. This application takes 4500 to 9000 rpm and delivers a steady output speed of 12,000 rpm, for 400 Hz ac output. Another typical application takes from 2160 to 3700 rpm and delivers a steady speed of 8000 rpm. These devices use a combination of planetary gearing and hydraulics for power conversion. State-of-the-art power range is from 30 to 150 Hp. These power conversion drives are extremely lightweight, on the order of 0.8 to 1.0 lb/hp, involve diameters and lengths from 10 to 18 inches.

These parameters will be used to examine the lower end of the application spectrum. This application for the SMHTC involves the difficulty of miniaturization and may not be a competitive alternative in the lower range of horsepower. The high speeds involved will ensure a minimum diameter of SMHTC, with fewer moving parts than the presently used maintenance-troubled mechanical-hydraulic unit. Present estimates indicate that the basic SMHTC weights will be competitive with the mechanical hydraulic drives. The development of small designs for low values of horsepower will require the systems analysis to estimate auxiliary requirements of cooling water, bearing oil, current collection clean-up, etc.

3.2.6 Homopolar Servomotor

Dc machines are often employed in closed loop control systems, particularly for the control of speed and torque where control is normally achieved by varying the field excitation or armature current or both. Dc machines are preferred for intermittent duty or where unusually high starting torque is required. The servomotor is required to produce rapid acceleration from standstill or near standstill conditions. For several reasons, the SEGMAG homopolar motor appears to offer potential for the rapid positioning of large inertia objects, including radar or other antenna arrays where variable directivity is required, rotating gun mounts or missile launchers, and for rotating devices where precision control is essential.

The figures of merit of a servomotor is given by T^2/J, a measure of how speedily the motor is able to respond (T is the value of torque, J the moment of inertia of the motor). A similar measure defined as "goodness" factor is T/J, an exact measure of the motor acceleration without load. Any factor which can increase the torque faster than it increases the square room of inertia can be utilized to improve the figure of merit for a servomotor. The SEGMAG homopolar servomotor is then a promising application. Since the torque is proportional to the armature and the power rate is proportional to the I^2R losses of the armature, the inherent high current characteristics of SEGMAG motors will contribute to the high T^2/J ratio. The increased power density for low weight and low inertia machines suggests that extremely precise control may be obtained in these applications.

Theoretically, the SEGMAG homopolar can be easily controlled to give variable speed and special torque characteristics at high efficiencies. The linear speed-torque relation could be obtained with minimum control equipment in this application.

3.2.7 Miscellaneous Applications

A number of areas exist in which research and development efforts have been conducted and reported upon in the technical community of the USSR. Several of these are listed below. The potential of such concepts appears high and worthly of further evaluation.

- Impact homopolar pulse generator with plasma current removal
- Ac homopolar generator as stable frequency source
- Low frequency ac homopolar generators for induction mixing of liquid metals
- Homopolar acyclic slip clutches and brakes
- Homopolar generator as acceleration sensor

Several areas which appear of extreme industrial interest involve the generation of large currents at low voltage. These applications are of interest to the national defense in many cases, including:

- Electrolysis of magnesium, sodium, aluminum, gold, silver, lead, copper
- Electrolysis of chlor-alki chemicals
- Electrolysis of water for constituent elements
- Electrowelding of large, seamless pipe
- Brushless exciters for large turbogenerators
- Motor applications for high torque attrition mills
- Motor applications for precision control as in steel rolling mills

SECTION 4

LIQUID METAL CURRENT COLLECTION SYSTEMS

4.0 OBJECTIVES

The specific objectives of this task are: 1) to review the state-of-the-art of liquid metal current collection system technology, 2) to identify preferred current collector designs by analytically investigating the complex electro-magnetic interaction and forces experienced by liquid metals in functioning collector systems under a variety of operating conditions, 3) to identify the operational problem areas which a successful liquid metal current collector must overcome to perform satisfactorily, and 4) to establish the constraints which the liquid metal handling and purification system will have to satisfy. (This and other aspects of liquid metals are discussed in Section 5.)

4.1 PRIOR AND RELATED WORK

For optimum utilization of a solid brush current collection system, it is necessary to consider selection of brush and ring materials for low friction and low contact voltage drop; brush geometries and holding mechanisms to provide a maximum number of active contacts; controlled atmosphere to provide low contact voltage drop, low wear rate, and low friction; and efficient utilization of cooling techniques. Many trade-offs will need to be made, e.g., between maximum current density and brush wear rate. Early studies with fiber-type brushes show an interesting potential for high-level current collection with this technology. Solid or fiber brush current collection systems are relatively bulky in size, however, and the installation volume required would significantly decrease the specific output sought in the proposed homopolar machines.

To accommodate for the continuing operation at the high current loads and high rotational speeds conceived for machines of the advanced design, it appears that liquid metal current collection systems have a higher potential for success than solid-type brushes. Current collection systems utilizing liquid metals are capable of transferring high magnitudes of electrical current. The need for "unflooded machine gap" liquid metal current collection systems is based on a necessity to reduce hydrodynamic, electrodynamic, and thermodynamic power losses. One of the most serious problems of the "unflooded gap" machine is confinement of liquid metal to the current collection zone. The confinement is challenged by gap tolerance, machine operating requirements, and magnetic field-electrical current interactions. A solution to this problem will likely involve uniquely shaped electrodes and, or, suitable gap seals. The need for liquid metal clean-up capability may be required to eliminate a possibility for "powder" formation and to retain the fluid's electrical conductivity and wetting ability.

4.2 CURRENT PROGRESS

4.2.1 Current Collector Systems

An investigation of available information pertaining to the application of solid-type brushes and liquid metals as current collectors for advanced design homopolar machines was made. The combined requirements of high peripheral velocities, up to 30,000 feet per minute (fpm), high current densities 2,000 amperes per square inch (apsi) and above, and small size are serious challenges to the use of current collection systems in homopolar machines.[1,2]* Ideally, the current collection system must perform with low power loss and long, trouble-free life.

4.2.2 Solid Brush Systems

Generally, the problem areas noted with solid brush systems were associated with generation of excessive power losses, maintenance of brushes and collectors due to wear and the large size of the collector system since acceptable current densities were relatively low (100-200 apsi)[3-7]. The electrical and mechanical power losses occur, essentially, at the sliding contact interface, resulting in high localized temperature at contact spots. Although the wear phenomena in sliding electrical contacts are rather complex, it has been established that wear rates for brushes accelerate rapidly when maximum temperature in the brush reaches about 500°C.[8]

The performance of solid brush collector systems may be improved by taking certain factors into consideration. Such factors would include 1) operation in non-oxidizing atmospheres, with suitable humidity levels,[9-12], 2) careful selection of brush-ring materials, 3) utilization of all available means for cooling, and 4) subdivision of larger brushes into a greater number of smaller ones. The idea of brush subdivision is carried essentially to the limit with carbon fiber or carbon-metal composite fiber brushes.[13] Experiments to date have demonstrated that reasonably long life can be achieved with these brushes operating at current densities to 500 apsi on copper rings in an air environment.[14,15]

It appears that the first problem which needs resolution is establishing the feasibility of steady-state operation of solid brush collectors at current densities in the 1,000, and higher, apsi range. To date, no development program has been initiated with this as its objective. Although the probability for achieving such a goal, with either solid brushes or fiber-type brushes, appears attractive, it also seems logical that any further consideration of the use of solid brush collectors for modern, high specific output homopolar machines must await the demonstration that the desired high current densities can be achieved.

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*NOTE: References are listed in Section 4.3.

4.2.3 Liquid Metal Systems

The major limitations of solid brushes, which prevent them from meeting the needs of an electrical current collection system for large homopolar machines, can be overcome by the use of liquid metals. Current collection systems utilizing selected liquid metals are capable of transferring very high magnitudes of electrical current across very small volumes.[16-18] To accomplish this task efficiently, however, it is necessary that the liquid metal be confined to thin ring-shaped volumes or annular channels which comprise the machine's current transfer or collection zones. Successful utilization of liquid metals employing this concept is seriously challenged by an ability to hold the fluid in the annular space under all operating conditions to be encountered. The natural alternative solution to this problem is to completely fill the machine with liquid metal. A major obstacle to using the "flooded gap" concept in large high-speed homopolar machines, is that hydrodynamic power losses created in the fluid during operation become prohibitively high. In general, the magnitudes of these power losses vary in linear proportion to the fluid's density and wetted contact area, to the cube of the slide velocity, and to a "friction coefficient" which depends on the Reynolds number and the Hartmann number.[19-22] Some reduction in this power loss may be obtained by selecting liquid metals possessing the desirable properties, such as the alloy sodium-potassium, NaK.[23] Even so, the large contact areas and high speeds imposed on any liquid metal selected to fill the gap of a large homopolar machine will cause excessively high shearing stresses and associated high power losses within the fluid. Since relatively high peripheral velocities are required of homopolar machines, it is necessary that the internal machine areas in contact with the liquid metal be minimized to achieve reasonable machine efficiencies. Consequently, the need for "unflooded gap" liquid metal current collection systems is based on a necessity to reduce hydrodynamic power losses associated with completely filled machines.

Although significant improvements in machine efficiency are achieved when utilizing the "unflooded gap" concept, power losses associated with the small fluid current collection volumes or zones are similar to those which accrue at the corresponding locations in "flooded gap" machines. In both cases, hydrodynamic, electrodynamic, and thermodynamic power losses are created because of velocity gradients, magnetic fields, and electrical load currents within the liquid metal contained between the moving and fixed electrodes. The relative magnitudes of these losses are influenced by the physical properties of the liquid employed, by the machine's electrical current, magnetic field, and speed, and by geometric factors.[24-25] General liquid power loss equations, which involve these parameters, have been developed.[26] An indication of loss magnitude may be obtained from a dimensionless parameter, δ, used in the equations.

Perhaps the most serious problem of an "unflooded gap" liquid metal current collector system is confinement of the fluid to the annular collection zone under all operating conditions. This is especially of concern in the case of horizontally-mounted machines. The confinement is challenged by necessary annular gap tolerances, machine operation requirements, and magnetic field-electrical current interactions.

The annular current collector gap must be sufficiently large to accommodate relative displacements of the electrode elements, required by manufacturing tolerances, differences in thermal expansion, and vibratory motions expected in large rotating machines. At standstill or under very slow speed running, where the centrifugal force is not sufficient to counterbalance the gravitational attraction, surface tension forces will not be sufficient to keep the liquid metal in the collector gap and the liquid metal will "drop out" of the gap, receding gradually from top to bottom.

Ambient axial magnetic field-load current interactions create Lorentz body forces which tend to move the collector fluid in the direction of rotation for a motor, but counter to rotation for a generator. Thus, the critical rotor speed resulting in liquid "drop out" is effectively lowered by the Lorentz body force in motor applications. If the motor is required to reverse its direction of rotation, however, either the excitation field or the load current must be reversed. Either action will cause a reversal of the Lorentz body force acting on the liquid. This will cause the liquid-metal's speed to decrease to zero, then attempt to increase in the opposite direction. During the transition period, "drop out" of liquid metal will become a problem and provision must be made to prevent it.

Another magnetic field exists in homopolar machines which works to expel liquid metal from the collector channel.[27] This is a self-induced field, created by load current in the rotor and stator conductors. The induced field is oriented in a circumferential direction and, when interacted with the load current, produces a Lorentz body pressure which tries to expel the fluid axially out of the collector gap.

In addition to loss of fluid from the collector zone in the form of large liquid quantities, loss can also occur in the form of aerosols. Aerosol formation is attributed to viscous working of the liquid metal, and the process is thought to be enhanced at elevated temperatures.

Another basic concern involving the reliability of liquid metal current collection systems over long time running is the maintenance of low electrical resistance within the fluid and low contact resistance at the electrodes. Both of these conditions appear to be associated with purity of the liquid metal, especially in the face of viscous working.[28] Of concern, with regard to volume resistivity, is a "change of state" phenomenon which has been observed with certain liquid metals.[29] Such transfer in physical state is manifested by the conducting fluid changing to an insulating "powder". This, of course, would render the machine inoperable, and that cannot be tolerated. Unclean electrode surfaces, initially or subsequently formed, may seriously inhibit "electrical wetting" and lead to increased contact resistance with the liquid metal.

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SECTION 5
MATERIALS STUDY

5.0 OBJECTIVES

The specific objectives of this task include: 1) the complete identification of materials requirements for the construction of a homopolar machine, including all metallic inorganic, and organic materials, 2) the assessment of potential long term materials compatibility problems with both liquid metals and cover gases under conditions of normal operation as well as during possible failure modes and routine or periodic maintenance situations, 3) the definition of other related or anticipated materials problem areas and the evaluation of possible means for their solution.

5.1 PRIOR AND RELATED WORK

Scientific study of those liquid metals which are of greatest concern to homopolar machines, namely NaK and GaIn, has largely concentrated on their usefulness as high temperature heat transfer media, as in fast breeder reactor technology. Consequently, much of the chemical and materials methodology which has been built up with these liquid metals involves information which is not directly applicable to the operating conditions of homopolar machines. Some extrapolation is,therefore, required, as well as some technique development, to produce a homopolar machine capable of sustained long term operation.

However, the reactive nature of both NaK and GaIn, especially with oxygen and water to form oxide coated aerosols and "black powder", place a premium on incorporating as much previous liquid metal technology and experience as possible into the design of a homopolar machine.

The General Electric Company (GEC) of England have developed a homopolar generator (16,000 amps at 8 volts) with GaIn current collectors and a continuous purification system, enabling the machine to operate for long periods of time. This achievement is a unique development for machines of this type. Westinghouse has requested permission to purchase a prototype generator from GEC to evaluate its performance and design, to gain practical information on GaIn technology, and to utilize it as a source of electrical current in experimental studies of model homopolar machine components.

5.2 CURRENT PROGRESS

5.2.1 General

The important materials problems associated with liquid metal current collection which have been identified and dealt with include: 1) long term chemical compatibility of structural materials with liquid metals and cover gases during normal operation as well as with cleaning solutions during machine maintenance, 2) the effect of water and oxygen outgassing rates from insulating materials on the selection of preferred choices yielding minimum liquid metal contamination rates, 3) impurity control in both cover gas and liquid metal as a means of prolonging functional component life, and 4) the definition of a machine design and construction philosophy which takes into account the needs of the liquid metal and cover gas system.

5.2.2 Materials and Compatibility Studies

A literature study of the compatibility of machine materials with various liquid metal current collection fluids was completed. In defining compatible materials, consideration was given to the reaction products which are generated during machine clean-up and decontamination. Since these products, i.e., hydroxides, alcoholates, and oxides, may form during machine clean-up they must also be considered from the materials compatibility viewpoint. In addition, the consequences of potential operating failure modes, such as internal arcing, must be considered when defining compatible materials. Therefore, tne establishment of acceptance criteria for all anticipated operating conditions for the various materials to be employed is being undertaken.

A literature survey has demonstrated that nearly all liquid metal work to date has involved its employment as a heat transfer agent. In such applications the liquid metal does not contact electrical insulation materials. AEC and NASA studies report liquid metal/ceramic insulator compatibility studies for thermionic and MHD application, but at concomitant elevated temperatures. This work is of some value to the selection of insulating materials for homopolar machines and was employed to give guidelines toward proper material selection. From this point of view, a list of candidate materials was prepared.

A number of construction materials are compatible with NaK at the temperatures (<200°F) which will be encountered in the machine. On the other hand, GaIn alloys are not compatible with many construction materials. Generally, Ga reacts readily with many metals and non-metals. Tungsten and tantalum exhibit the greatest resistance to attack by gallium.

A literature review has revealed that liquid metal embrittlement of structural materials can be an expected problem when such materials encounter GaIn and NaK. These problems are less severe with NaK than with GaIn liquid metal alloys. As a consequence, material combinations which appear compatible to machine operation as a result of literature/ data reduction may be incompatible from a liquid metal embrittlement

viewpoint. The synergistic effects of liquid metal/structural material interaction and the stresses involved in the materials under operating conditions must be experimentally determined. These include potential effects on such mechanical properties as strength, ductility, etc.

If necessary, incompatible (corrosion) structural materials may be employed provided they are protected from the GaIn environment. This may be accomplished by protecting these materials with coatings of compatible materials such as tantalum or tungsten. These metals may be chemically vapor deposited (CVD) on the structural materials (or on the copper conductor material), or applied by such techniques as co-extrusion or hot isostatic pressure welding.

- Chamfer or round all edges, and fill all corners to a radius to facilitate machine decontamination.
- Provide cover gas inlet lines at the periphery to the current collector region to sweep away gaseous contaminants during operation.
- Provide for internal heating or heated cover gas to drive off moisture and absorbed air after machine decontamination.
- Provide inflatable collar seal surfaces at each rotor end to permit machine evacuation and degas by vacuum pump.

These and similar considerations will be of great value in maintaining purity of machine cover gases and NaK liquid in the current collector region.

(2) Utilize a positive pressure gradient inert cover gas inside the machine housing to prevent the entrance of atmospheric contaminants, such as oxygen or moisture, during machine operation.

(3) Continuously recirculate the cover gas through an external purification loop to remove outgassed and in-leakage contaminants to the machine housing and liquid metal current collection area.

(4) Continuously recirculate the liquid metal in the current collection area through an external purification loop to remove oxides which form in the current collection area.

Studies indicate that total system contamination control as described above can be maintained through currently available technologies. Small problems in determining efficiencies for low temperature operations and interfacing of cover gas and liquid metal systems in the machine current collection region are currently being resolved. Phase II experiments necessary to obtain this resolution are currently being designed.

SECTION 6

SEGMENTED MAGNET HOMOPOLAR MACHINE DESIGN

6.0 OBJECTIVES

The objective of this program is to demonstrate the segmag concept used in the SMHTC and to provide a test vehicle for current collection technology developed in subassembly testing. The demonstration unit will subject the current collection system to current densities, leakage flux and other conditions associated with operation in a machine atmosphere. In addition, the unit will provide for long term testing of both the current collectors and the machine.

6.1 PRIOR AND RELATED ART

The segmag concept was developed to provide a high performance DC machine without requiring superconducting magnet excitation. This low reluctance machine, using room temperature excitation, has capability for high output per unit weight and volume. The modular construction allows for higher outputs by using many modules hooked up in series. The characteristics of this machine are being thoroughly investigated in another contract (N000 14-72-C-0393).

6.2 CURRENT PROGRESS

A 3000 HP, 3600 rpm two-magnet segmag design is nearing completion. The design will provide maximum flexibility in the areas of current collection, containment seals and liquid metal injection. This will allow for testing of various concepts in these areas during the machine test program. The machine rotor will be designed for rotational speeds of up to 8000 rpm to provide testing flexibility at higher relative speeds. The design has not been optimized for maximum output per unit weight or volume, but for maximal flexibility.

SECTION 7
SEAL STUDY

7.0 OBJECTIVES

The seal study associated with this program had two primary objectives: 1) to review the current state-of-the-art of seal technology and identify those locations in homopolar machines requiring seals, and 2) design a test apparatus capable of evaluating the performance of various seal concepts under operating conditions anticipated in homopolar machine applications.

Two primary seal requirements were identified. These were 1) that location where the shaft penetrates the containment vessel of the machine, and 2) a seal associated with the liquid metal current collector itself. In addition, since homopolar machines must operate in an environment completely devoid of oxygen and moisture, a specific seal material requirement exists since conventional seals, such as carbon-graphite, lose their low friction-wear characteristics in such an environment.

A discussion of the results of this effort will be found in the following sections.

7.1 PRIOR AND RELATED WORK

Continuing demands for higher efficiency and higher performance of modern machinery; such as, gas turbines, compressors, and other types of rotary gas-handling equipment, have generated increased attention to the problems of seal performance in these applications. Clearance seals, by their very nature, yield leakages that are unacceptable in many of these installations. For this reason, considerable effort has been devoted to the development of high performance, low leakage, contact-type seals for use in critical applications. A circumferential seal is one such design that exhibits the ability to not only withstand high-velocity rubbing at their primary sealing surfaces, but also to provide a high degree of sealing ability. In addition, it allows for considerable relative axial motion between the rotating and stationary members of the machine. The general configuration of a typical circumferential seal consists of relatively stationary segmented rings which mate with a rotating member on their bore. The rings are loosely keyed to the stationary member by rotation locks. Circumferential garter springs are used to maintain contact under static conditions. Under dynamic conditions, incorporation of appropriate seal life configurations results in the separation of the sealing surfaces from the rotating member by hydrostatic means. The amount of separation is in the order of 100 to 500 microinches. Seals of this type have provided 4,000 to 5,000 hours of operation at surface velocities of about 450 ft/sec. Gas leakage rates fall in the range of 0.1 to 0.3 SCFM.*

*Standard Cubic Feet Per Minute

The second major category of contact seals is the face-type, or mechanical seal. Completmenting the circumferential seal, the face seal is designed for applications requiring a high order of sealing effectiveness where axial motion between shaft and casing is limited. Unlike the circumferential seal, the face seal can be made to accommodate fluids with practically no regard to their viscosities. The conventional type of face seal is composed of a seal ring that is keyed by a rotation lock to a stationary housing. This seal ring contacts a shoulder that is constrained to rotate with the shaft. Primary sealing occurs in the radial plane of relative motion between the shoulder and a projecting dam on the seal ring. A secondary seal - in many cases an elastomeric, O-ring type seal - is located between the seal ring and the housing to which it is keyed. To maintain contact between the primary sealing members, an axial driving force is required to move the seal ring. The use of axial springs to supply this driving force is most common. Current practice employs this type of seal for confining both gases and liquids. For example, high-speed, industrial, face-type air seals have demonstrated their ability to provide several years of operation at surface velocities of nearly 300 ft/sec. The seals have demonstrated their ability to accommodate pressure differentials ranging from 10 psi to 135 psi without either excessive wear or high leakage. Dynamic air leakage at 30 psig, for example, is well below 0.3 SCFM.

High-speed industrial oil seals have provided successful operation for years in oil refinery compressor operation at surface velocities of 180 fps. Oil leakage in the order of 30 to 400 cc/hr (depending on speed) are easily accommodated by appropriately designing wind-back seals and drainage ports.

7.2 CURRENT PROGRESS

7.2.1 General

A literature search was performed to survey the current state-of-the-art of seal technology. The search emphasized key words such as dynamic seals, stable seals, pumps, cover gas closures, and visco seals. The following discussion will attempt to cover salient points pertinent to current seal applications in hostile environments, such as no-moisture conditions and liquid metals.

7.2.1.1 Shaft Seals

In work conducted under the CANEL project(1)*, a long-life sealing system for oil-lubricated, ball-bearing supported shafts of high temperature, high speed, liquid metal pumps was developed. Based on wear results of long endurance tests, an operating life of 100,000 hours for the sealing system was estimated. In an endurance test program involving eleven

*NOTE: References are in Section 7.3.

separate units with tests of up to 1500 hours duration, excellent results were achieved with total seal wear of 0.002 inch and oil leak rates as low as 0.004 cc/hr under a differential pressure of 17 psi. The pumps were operated at speeds up to 8500 rpm and circulated liquid metal (lithium or sodium-potassium alloy) at temperatures up to 1600°F. A dry gas seal developed during this program accumulated more than 20,000 hours of excellent performance. It was found, however, that to maintain this performance a minimum shaft speed of 2000 rpm was required. Table 1 presents a summary of these prototype seal results.

The Los Alamos Scientific Laboratory[2] has detailed the performance of oil-lubricated mechanical face seals used in their 2000 kilowatt Sodium Test Facility. The unit employed multistage centrifugal pumps with sodium-lubricated hydrodynamic shaft bearings. The primary pump was operated for a period of 11,920 hours, with no downtime for maintenance, after the first two weeks of operation. The secondary pump was operated for 13,374 hours, with no downtime for maintenance. No undue wear or evidence of incipient failure was revealed upon post-operational inspection.

During the operation of the sodium pump, the oil reservoir was pressurized to 5-10 psi more than the sodium cover gas. This pressure differential ensured adequate lubrication of the seal faces. Oil that flowed past the seal faces was collected in an external reservoir, the volume of which was periodically measured to provide an indication of seal oil consumption. Table 2 presents these measurements for approximately one year of pump operation. It will be noted from these data that oil consumption, particularly in the primary pump, was quite irregular during the first seven months of operation. This irregularity was attributed to particles of foreign matter (iron oxide) lodging between the seal faces and causing irregular seating until the particle was discharged and the seal faces "worn in" again.

During the final two months of this test, the primary pump was equipped with an experimental, helium-lubricated shaft seal assembly. This seal operated satisfactorily for approximately one month, consuming about 5 std ft^3/day of helium. After this period, however, the helium consumption gradually increased, becoming excessive during the final month of test operation.

The Hallam and Fermi[3] pumps use face-type shaft seals to contain the low pressure (1/2 psi) cover gas. No shaft seal problems had as yet been experienced at the HNPF, but excessive seal leakage (oil leakage) had been found to be a problem at the EFAPP. Both plants use oil-lubricated rubbing seals, although the EFAPP primary pumps used a non-hydrogenous oil (fluorolube), which does not have lubricating characteristics as good as the mineral oil used at Hallam. Maintenance life for these oil-lubricated type face seals was reported as six months to one year being typical.

Pumps developed during the Aircraft Nuclear Propulsion Development Program[4] utilized both gas as well as oil-lubricated shaft seals. The shaft seal between the purge cavity and the sweep cavity was a gas-to-gas seal which

TABLE 7-1

SUMMARY OF PROTOTYPE SEAL ENDURANCE TESTS

Test Unit	SRE-1	SRE-2	LP-IC	LP-ID	LP-IE	LP-IF	LP-11	NP-IC	NP-ID	NP-IE	LMB-1
Test Conditions											
Speed, rpm	5700	5700	4930-5250	5000	3600-4000	5000-8000	5000	3609-4750	5800	3600-5800	8000
Environment-Gas	He	He	He	He	He	He	He	A	A	A	He
-Liquid Metal	—	—	Li	Li	Li	Li	Li	NaK	NaK	NaK	Li
Pump Temp., °F	1150c	1200b	1000	1000	900	1000-1625	1000-1200	700	695-1400	695-1200	625
Total Hours	15,027	10,364	10,292	6,696	10,245	6,600	10,112	10,963	3,011	8,113	10,031
Upper Oil Seal											
ΔP, psi	17.0	17.0	17.0	12.0	17.5	17.5	20.0	8.0	17.5	5.3	17.5
Temp., °F	215-150	220-175	177-245	135-277	204-293	207-298	55-182	—	—	64-141	—
Leakage, cc/hr	.05	1.5	47	5.3	.04	.06	54	004	1.3	1.1	—
Wear, inches-											
-Rotor	.0001	.0001	.0001	.0001	.0001	.0002	.0001	.0001	.0001	.0001	a
-Stator	.0001	.0011	.0001	.0001	.0001	.0007	.0001	.0001	.0001	.002	a
Lower Oil Seal											
ΔP, psi	2.0	2.0	2.5	2.5	3.0	2.0	2.0	2.0	2.5	8.0	2
Temp., °F	285-215	—	140-162	131-150	159-232	121-162	66-119	—	—	—	—
Leakage, cc/hr	19	0	0	.08	.01	0	6	.01	57	.07	.45
Wear, inches-											
-Rotor	.0001	.0001	.0001	.0001	.0001	.0002	.0001	.0001	.0001	.0001	a
-Stator	.0001	.0001	.0001	.0001	.0001	.0004	.0003	.0001	.0001	.0001	a
Dry Gas Seal											
ΔP, psi	1.0	1.0	0.5	0	0.5	0.5	0.4	0.5	0	0.4	0.5
Temp., °F	550-375	600-525	201-335	--	245-345	235-392	200-300	—	—	201-300	235 250
Leakage, sci/hr**	.025	.01	1	d	1	1	1	1	d	1	1
Wear, inches-											
-Rotor	.0085	.001[c]	.0088	.0104	.0105	.0032	.006	.0105	.0094	.0059	.00001
-Stator	.010	.003[c]	.018	.007	.0100	.0068	.0028	.011	.014	.0024	.00003

*Reference 1

[a] Disassembly of this unit incomplete at time of this report

[b] Pot temperature simulating pump thermal condition

**Std in^3/hr

[c] Light oil film was found on seal faces at post test inspection

[d] Excessive leakage occurred with a finite pressure differential

TABLE 7-2-OIL CONSUMPTION OF LOWER PUMP* SEALS

Month	Primary Pump	Secondary Pump
May 1960	16 cc	59 cc
June 1960	15	31
July 1960	79	40
August 1960	143	25
September 1960	69	29
October 1960	376	33
November 1960	122	36
December 1960	127	93
January 1961	19	72
February 1961	29	64
March 1961	27	60
April 1961	16	92
TOTAL	1,038 cc	634 cc

*Reference 2

received no coolant or lubricant. Seal face materials selected for this seal were Kenametal Cermets K-162B and K-96 for the stationary and rotating rings, respectively. The shaft seal between the purge cavity and the bearing cavity was cooled by an oil spray. In this case, both the stationary and rotating seal faces were fabricated from Carboloy 44A. To minimize seal distortion and to ensure even cooling, the seal assembly received oil from six equally spaced jets. In addition, oil that was sprayed on the seal also impinged on the shaft directly above the seal assembly, thereby removing heat conducted up the shaft from the impeller. Seal faces were flat to within one light band of helium and were loaded to 15 lbs total force by means of a bellows spring.

7.2.1.2 Liquid Metal Current Collector Confinement Seals

Mechanical contact seals are considered as candidates for confining the liquid metal current collector in the collection zone under machine operating conditions involving low rotating speeds (low surface velocities) and at standstill. Since these contact-type seals would be in intimate contact with the liquid metal, considerable attention must be devoted to the compatibility of the seal material with the fluid being sealed. For example, sodium-potassium alloys are quite active chemically and may inter-react with conventional carbon-graphites normally used in contact-type seals at the operating temperatures estimated in the collector zone. In addition, the operating temperature, and in turn, the wear rates of contact-type seals increases rapidly with rubbing velocity. For this reason, a technique must be developed for the disengagement of seal surfaces when operating speeds reach a level sufficient to contain the liquid metal by other means.

Non-contact type seals are defined as those which operate with the seal faces separated by a film of the fluid being sealed. Separation is achieved through either hydrostatic or hydrodynamic means. In the case of the homopolar machine, pressurized liquid metal would generate a force on the seal face sufficient to lift the seal from its mating runner by a minute amount. Prevention of rubbing contact between the seal faces by this technique provides a means for eliminating seal wear at surface velocities far greater than is possible with contact-type seals. Non-contact seals, however, exhibit significantly higher leakage rates than those realized with a rubbing contact seal.

7.2.2 Seal Test Rig

Two test rigs have been designed that will be capable of evaluating seal performance under conditions simulating those anticipated in homopolar machine operation. The test stands will be capable of operating various seal configurations over a 0 to 7000 rpm speed range in an inert, bone-dry environment. Leakage rates, operating speeds, and seal temperatures will be continuously monitored. One test rig will be utilized for evaluating the effectiveness of various seal configurations suitable for use as shaft/containment vessel seals. The second apparatus will be used for studying

various sealing techniques designed to confine the liquid metal current collector to the collection zone under low speed operation and at full machine stop. Reversing and jog capabilities have been designed into the rigs. Components of these test devices are currently being detailed.

7.3 REFERENCES

1. "Summary of Shaft Face Seal Development Program," AEC Research and Development Report No. TIM-909, July 15, 1965.

2. "Sodium Pumps in the Los Alamos 2000 Kilowatt Sodium Test Facility," Milton, B. J., Report No. LA-3782, December 21, 1967.

3. "Sodium Pump Development and Pump Test Facility Design," Westinghouse Atomic Power Division, Report No. WCAP-2347, August, 1963.

4. "Design Summary Report - LCRE Secondary Coolant Pump and Sump," AEC Research and Development Report No. PWAC-385, Contract AT(30-1)-2789, January 10, 1964.

SECTION 8

PLAN FOR PHASE II

8.0 OBJECTIVES

A plan shall be evolved to complete the development of the segmented magnet homopolar torque converter. This plan will identify all of the technical problems to be solved, the research and development tasks required to solve these problems, and the resources and manpower required to complete the development.

8.1 CURRENT PROGRESS

Work has been initiated on the plan for the Phase II effort.